Accelerator technologies for EUV or Soft X-ray Lithography

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20 years experiences since development
of superconducting synchrotron
X-ray lithograph source
AURORA

20 years experiences

AURORA was not adapted by lithography because,

I. 1W flux was not enough

10W for proximity, 1 to 10 KW for projection is necessary

II. If source is large and expensive, by the failure of 1 machine, whole process will be stopped!

Downsizing and cost down is necessary

III. Proximity projection is failed in mask correction technology.

Shifted to Laser or e-beam plasma EUV

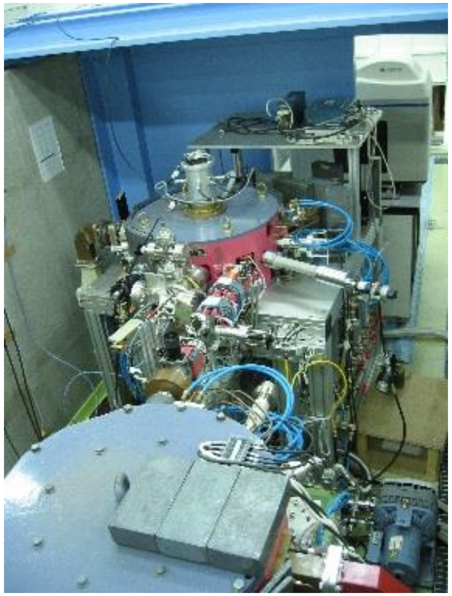
IV. MTBF was not enough.

Number of components should be reduced. SuperC technology is troublesome

I started working for normal conducting, low energy synchrotron technology 20 year ago

20 MeV

6MeV



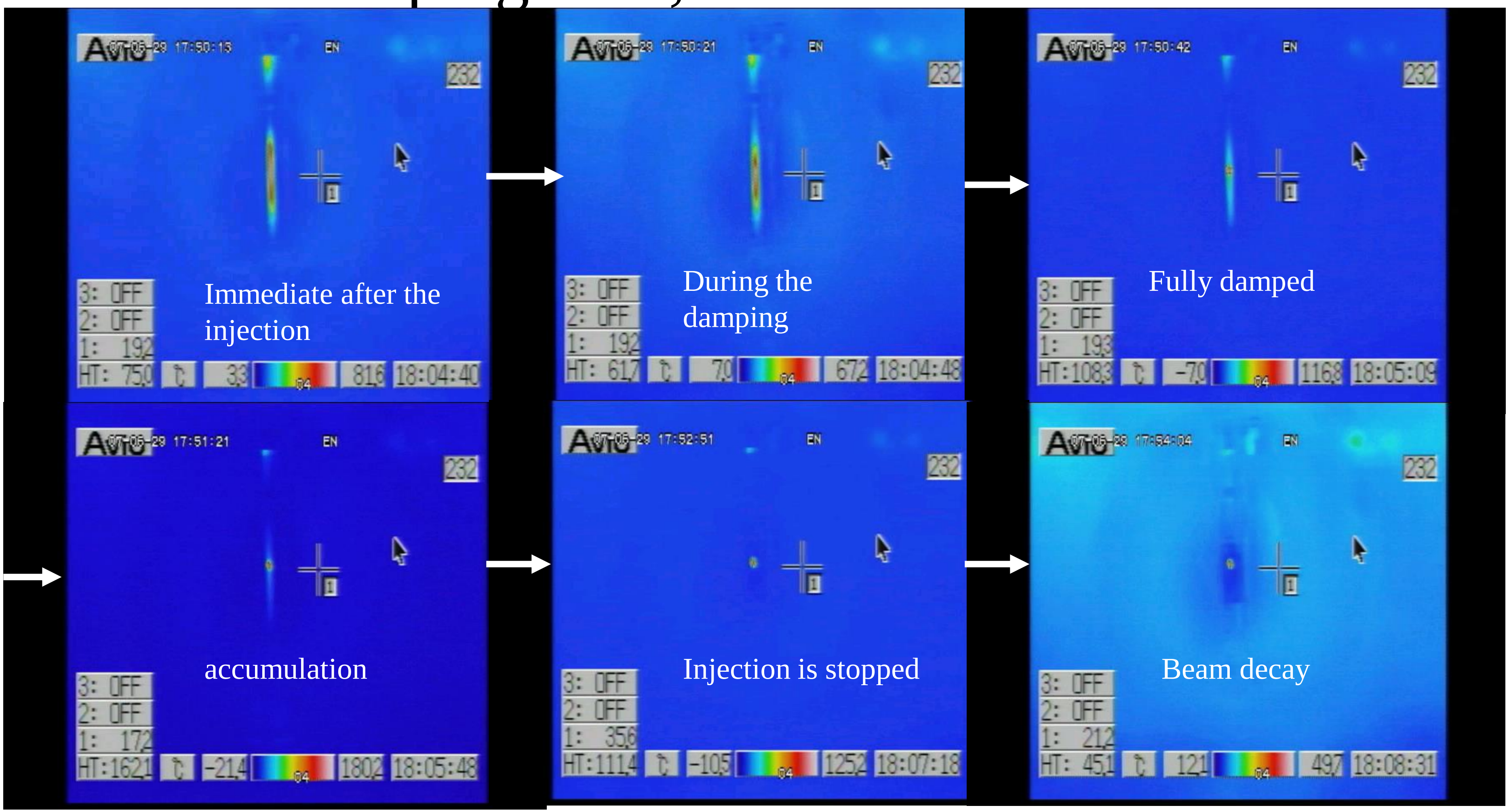
4MeV

These machines are completed and regularly used. CV4 is delivered to Hitachi for ultra fine resolution CT

MIRRORCLE is a real storage ring

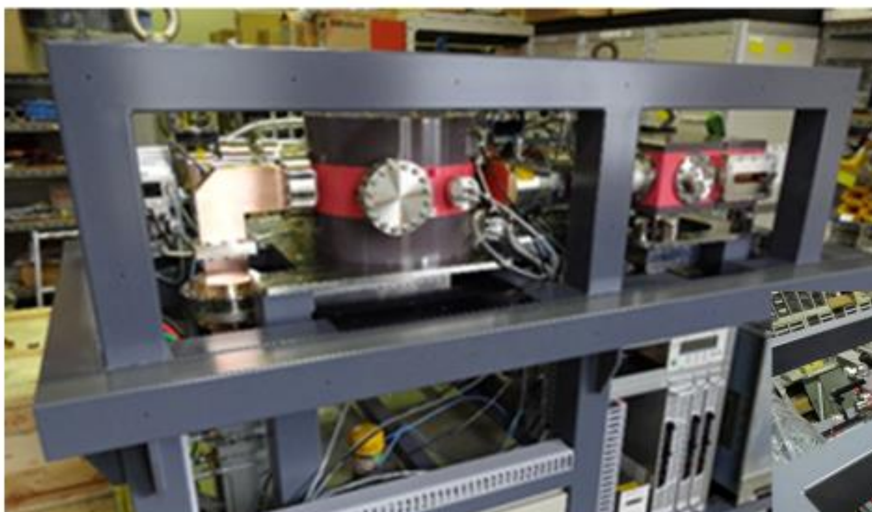
4A beam current is accumulated

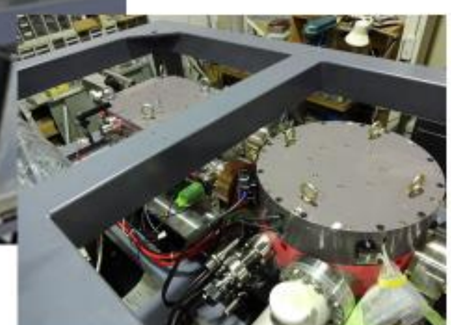
10ms damping time, 1min lifetime is recorded



By success in CW top-up injection we are able to obtain desired high power EUV or X-ray flux!

Synchrotron MIRRORCLE-CV4 HP model produced for HITACHI Ltd.





Provide 10μm space resolution CT!

In this talk we focus on·····

- Introduction of Synchrotron-Cherenkov radiation for EUV and soft X lithography.
- 20 MeV tabletop synchrotron can generate 1KW EUV or soft X.
- 20 MeV synchrotron-Cherenkov Laser for 10KW.
- Comparison with other sources such as X FEL and ERL

How to generate EUV o

> use target in

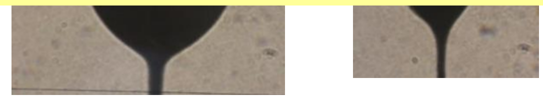
Important note!

Target last permanently.

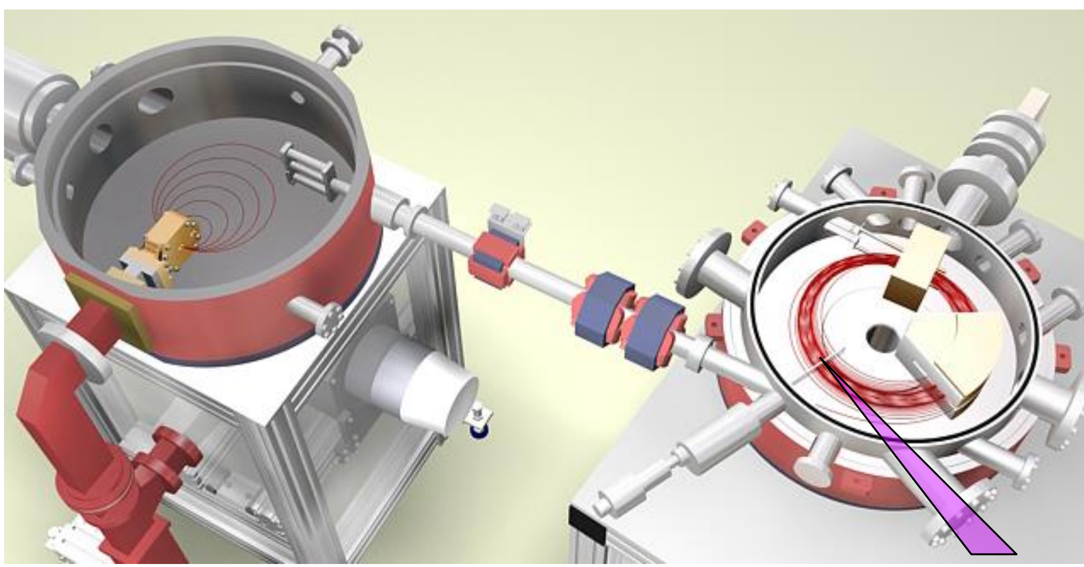
Deblis never happen because

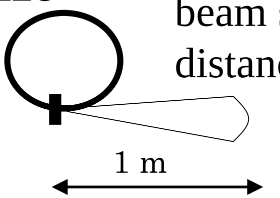
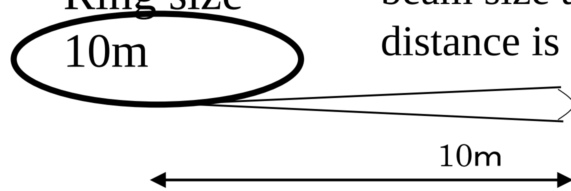
plasma is not generated.

CNT weave or yarn is used for EUV or soft X generation

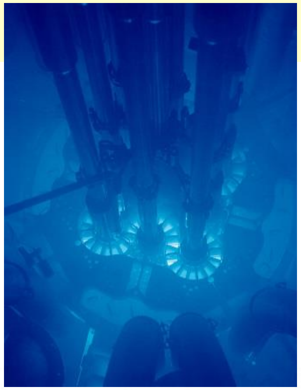


40μ W or 10μ Cu sphere glued on 5.5μm CNT wire are used for hard X-ray generation



SC radiation by 1 target with 20MeV ring	Undulator radiation by 300 MeV ERL
$10^{-3}\times100\times0.1[A]/1.6\text{x}10^{-19}$ $= 6.25\times10^{16}/50\text{mrad}^2$	$10^{-5}\times100\text{x}0.1[A]/1.6\times10^{-19}$ $= 6.3\times10^{14}/1.3\text{mrad}^2$
Ring size 1m  beam size at 1m distance is 50mmϕ	Ring size 10m  beam size at 10 m distance is 13mm
Beam line can be 1 m We can collect whole EUV radiation by mirror	Beam line you need 10m due to thick concrete wall
Brems total radiation yield/1mm thick target/1 electron : 10^{-3} photons／e, 0.1% band, mm target **TR or Cherenkov gives 100 times more** > 10^{-1}	Total radiation yield/1mm trajectory/1 electron : 10^{-5} photons／e, 0.1% band, mm trajectory **Undulator gives 100 times more.** **> 10^{-3}**
Average beam current 100mA	Average beam current 100mA

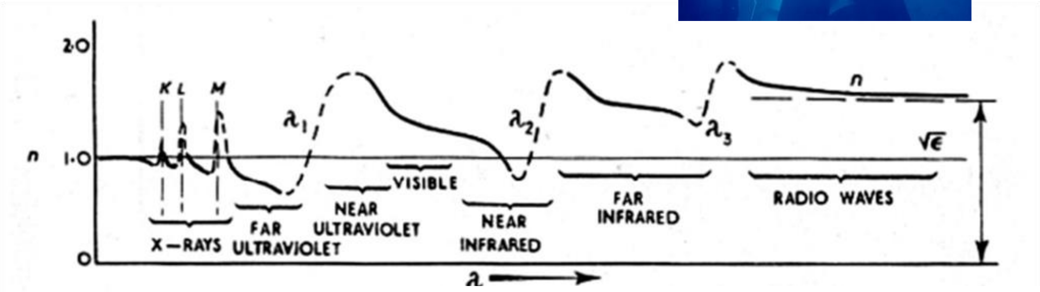
Either Cherenkov or TR radiation is the mechanism to be used



Cherenkov radiation occur when $n=1+\Delta n>1$

The radiation spread θ: $1/\gamma < \theta \sim 2\Delta n$ hollow cone

In EUV and X-ray region,
Spectrum is monochromatic.
It is coherent radiation

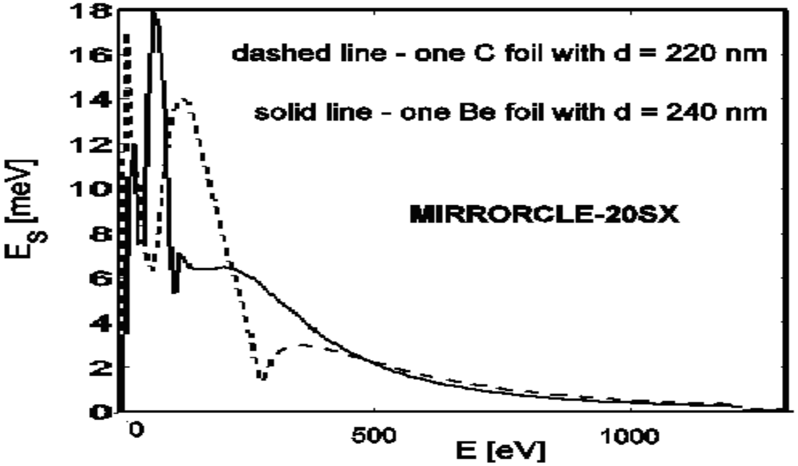


Transition radiation occurs
at the boundary of two medium

The radiation spread: $\theta \leq 1/\gamma$ hollow cone

Spectrum is continuous

$$\gamma \cdot \hbar\omega_p$$



Cherenkov radiation under magnetic field

It is called Synchrotron-Cherenkov radiation.

It is neither Cherenkov nor Synchrotron

The angular distribution of synchrotron-Cerenkov radiation

T. M. Rynne, G. B. Baumgartner, and T. Erber

J. Appl. Phys. 49(4), April 1978, p. 2233

Given formalism is same for SR except the refraction index n≠1

$$I(\omega,\theta)=\left(\frac{e\omega}{c}\right)^2 \lambdabar_c \frac{E}{mc^2}\frac{H_{cr}}{H}\left[[\beta J_\nu'(\nu\beta n_r \sin\theta)]^2 + \left(\frac{\cot\theta}{n_r}J_\nu(\nu\beta n_r\sin\theta)\right)^2\right];$$

for Δn << 1 (n=1+Δn)

$$\frac{d^2N}{d(\hbar\omega)\,d\psi}=\frac{2\alpha}{mc^2}\frac{L}{\lambdabar_c}\left(\frac{2}{\nu}\right)^{1/3}\left\{[\mathrm{Ai}'(\xi)]^2 + \left[\psi\left(\frac{\nu}{2}\right)^{1/3}\mathrm{Ai}(\xi)\right]^2\right\},$$

SR formalism is given for $(mc^2/E)^2 - 2\Delta n + \psi^2 > 0$

$$\frac{d^2N^s}{d(\hbar\omega)\,d\psi}=\frac{\alpha}{3\pi^2}\frac{L}{\lambdabar_c}\hbar\omega\frac{mc^2}{E^3}\frac{H_{cr}}{H}\left[1+\left(\frac{E}{mc^2}\psi\right)^2\right]^2 \times\left(K^2_{2/3}(\zeta^s)+\frac{(E\psi/mc^2)^2}{1+(E\psi/mc^2)^2}K^2_{1/3}(\zeta^s)\right)$$

SC formalism is given for $(mc^2/E)^2 - 2\Delta n + \psi^2 < 0.$

SC spectrum (1.13a) then exhibit an oscillatory behavior. It is convenient to introduce a new variable analogous to Eq. (2.1b),

$$\zeta=\tfrac{2}{3}(-\xi)^{3/2}; \tag{2.7}$$

since the limit $H\to 0$ is linked with the limit $\zeta\to\infty$, the spectral form (1.13a) can be replaced by the asymptotic estimate

$$\frac{d^2N}{d(\hbar\omega)\,d\psi}\approx\frac{2\alpha}{\pi mc^2}\frac{L}{\lambdabar_c}\left\{\left[2\Delta n-\left(\frac{mc^2}{E}\right)^2-\psi^2\right]^{1/2} - \frac{2\Delta n-(mc^2/E)^2-2\psi^2}{[2\Delta n-(mc^2/E)^2-\psi^2]^{1/2}}\sin^2\left(\zeta+\frac{\pi}{4}\right)\right\}, \quad \zeta\gg 1. \tag{2.8}$$

Oscillatory behavior appears beyond the SR regime $\psi > 1/\gamma$

The basic SC spectrum assumes a particularly simple form in case $\xi \gg 1$ [cf. Eqs. (1.13b), (2.4), and (2.14)]:

$$\frac{d^2N}{d(\hbar\omega)\,d\psi} \approx \frac{\alpha}{2\pi mc^2}\frac{L}{\lambda\!\!\!^{-}_c}\frac{(mc^2/E)^2 - 2\Delta n + 2\psi^2}{[(mc^2/E)^2 - 2\Delta n + \psi^2]^{1/2}} \times \exp\left\{-\frac{2\nu}{3}\left[\left(\frac{mc^2}{E}\right)^2 - 2\,\Delta n + \psi^2\right]^{3/2}\right\}. \qquad (2.18)$$

For appropriate choices of the index, such as $\Delta n \sim -\omega^{-2}$ [cf. Eq. (3.1a)], Eq. (2.18) displays the low-frequency damping which is characteristic of SC radiation.[3] Clearly, the intensity decreases for larger opening angles: In particular, the angle at which the intensity has diminished to one half the peak value is approximately given by

$$\psi^2_{1/2} \sim \frac{0.7(mc^2/\hbar\omega)(H/H_{cr})}{[1 - 2\,\Delta n(E/mc^2)^2]^{1/2}}.$$

In the index-dominated regime (2.15), this estimate can be sharpened to

$$\psi^2_{1/2} \sim \frac{0.5}{(-\,\Delta n)^{1/2}}\frac{(mc^2)^2}{E\hbar\omega}\frac{H}{H_{cr}}, \qquad (2.20)$$

which shows that *increasing* values of the index tend to *reduce* the angular dispersal of the radiation. Since index variations of this kind can be engendered by vacuum polarization, it is possible that novel focusing effects might be associated with pulsar emission.[3]

Cosθ=1/nβ

CR regime

SCR regime

SR regime

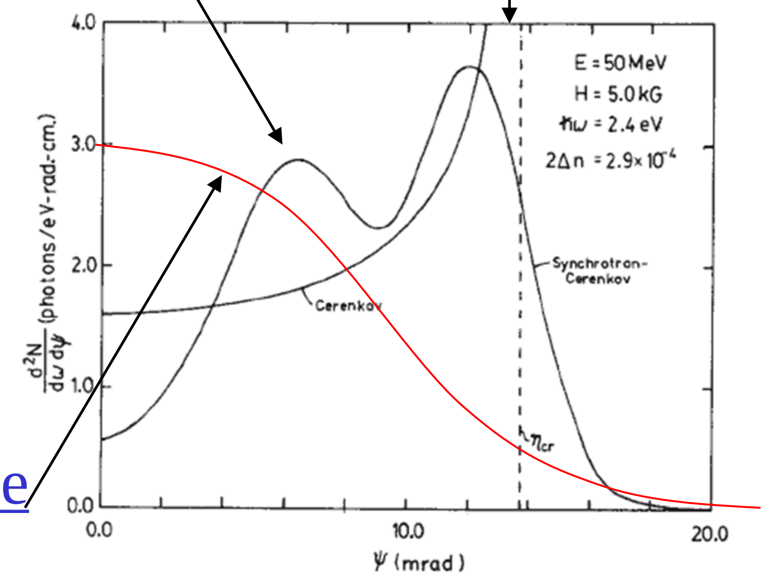


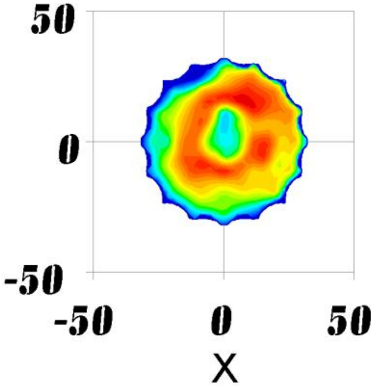
FIG. 9. Striations on the Čerenkov branch.

Interference of Cherenkov and SR appears

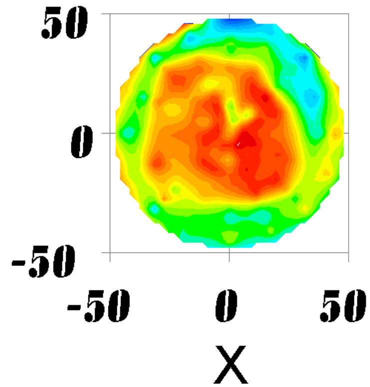
J. Synchrotron Rad. (2011). 18

Measurement of angular distribution of soft X-ray radiation from thin targets in the tabletop storage ring MIRRORCLE-20SX

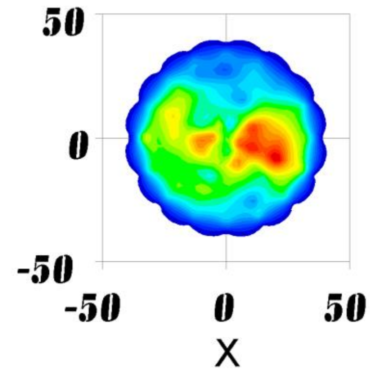
Hironari Yamada et al.



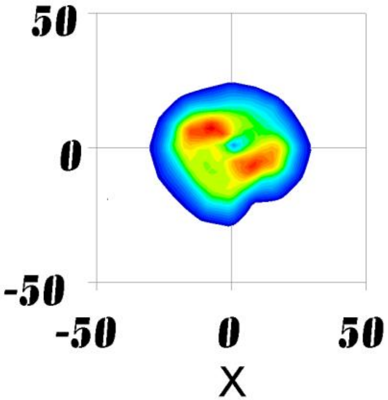
5 μm thick Mo sheet



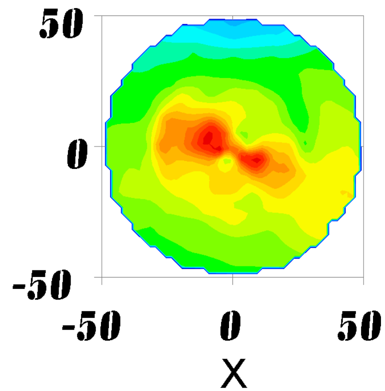
150 μm dia. Sn wire



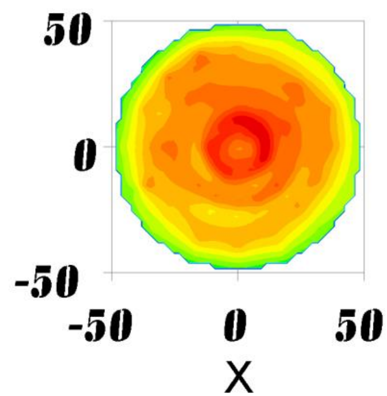
385 nm thick Al strip



15 μm thick CNT yarn

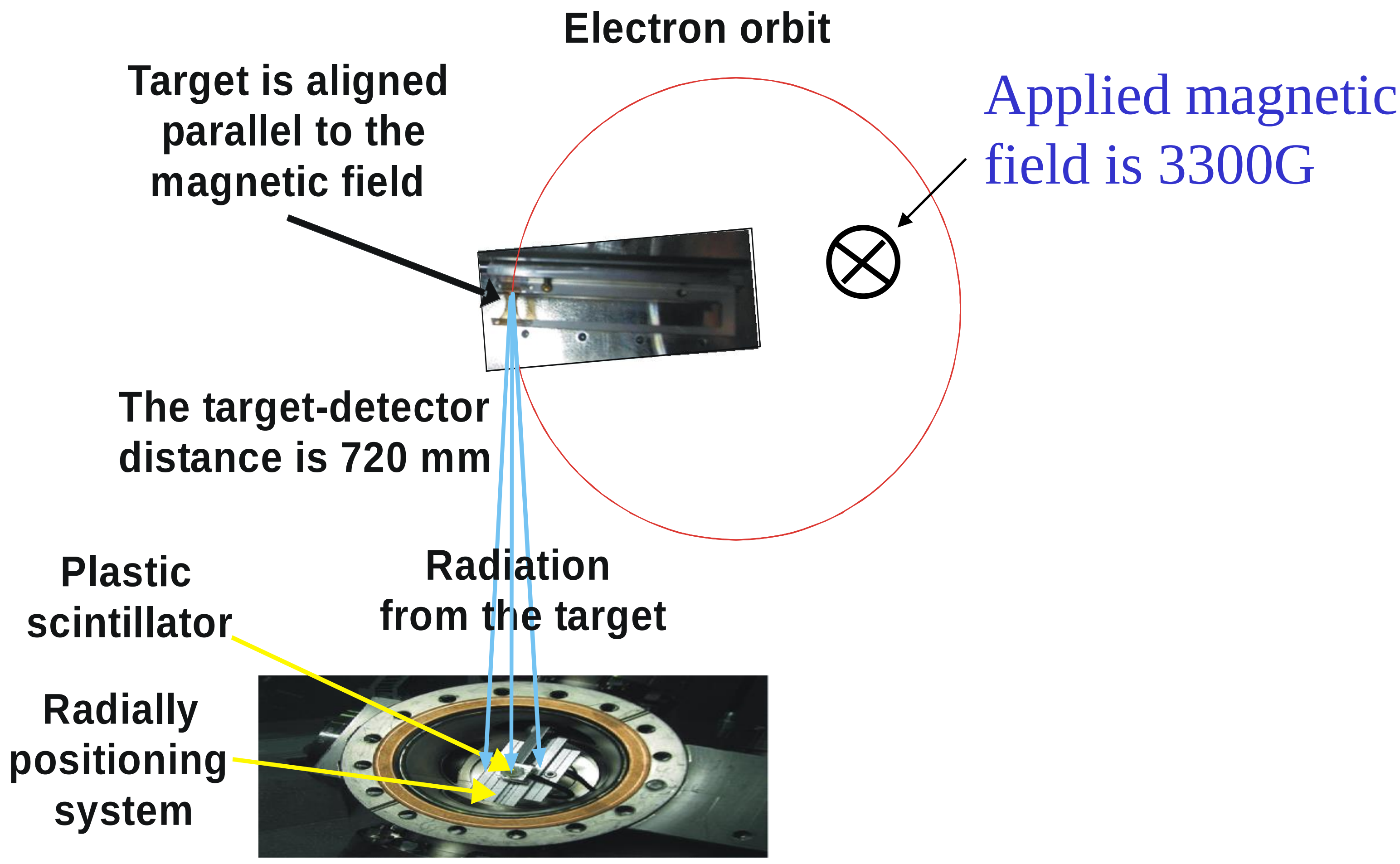


55 nm thick DLC strip



55 nm thick DLC strip with 385 nm thick Al filter

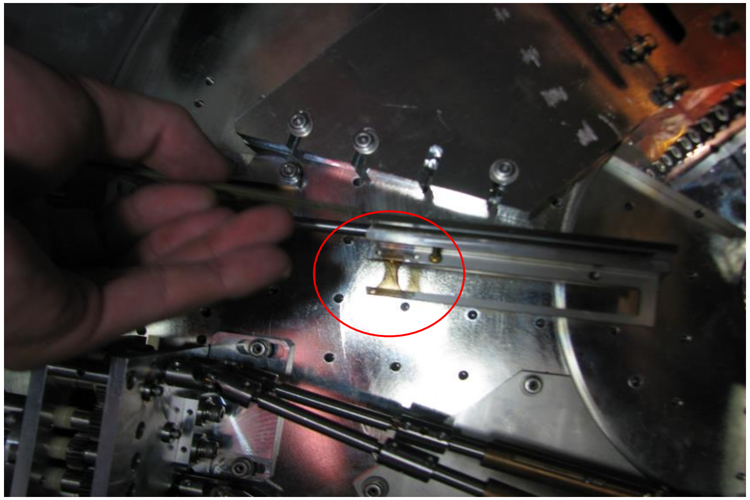
Experimental set up

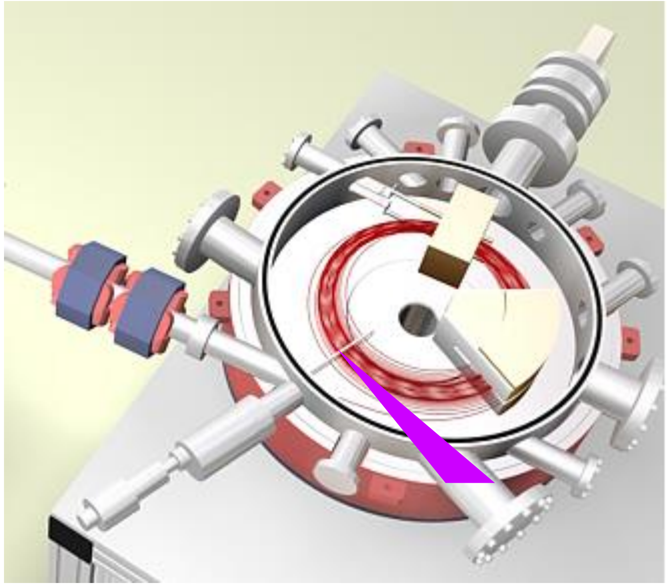


The scintillator scans in the plane perpendicular to the median plane of the electron orbit

State of art technology 1

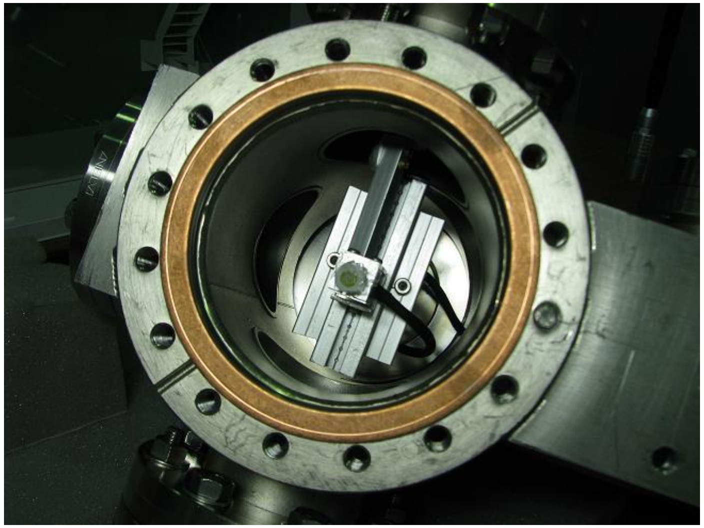
- The EM radiation yield from 100nm thick CNT yarn must be very weak.
- If thick target is used, soft X-ray is captured inside of target.
- Electrons are hitting target every 1.5ns repeatedly in the storage ring.
- Electron penetrate the thin target and re-circulate.
- Gain 1KW energy by RF cavity
- The beam current is 40A

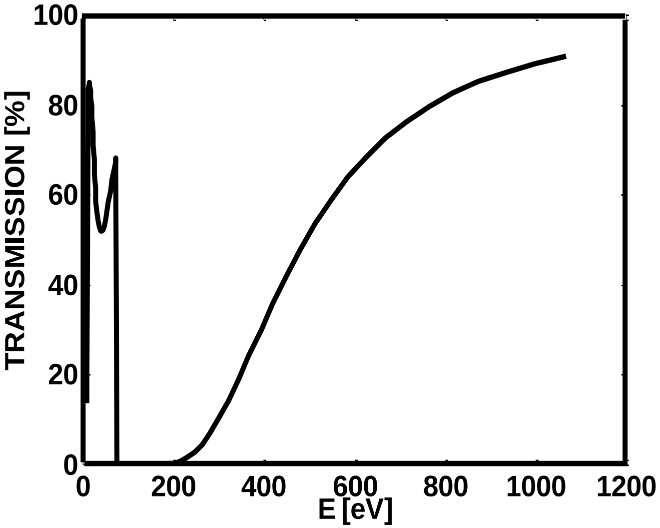




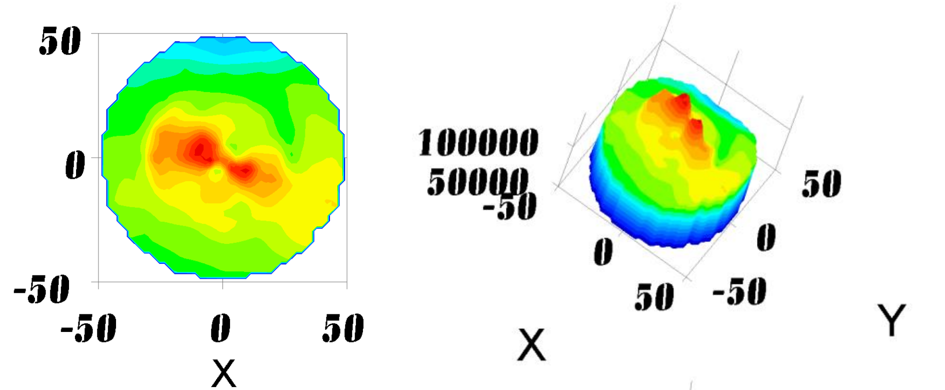
State of art technology 2

•Plastic scintillator (PS) is connected by plastic fiver to photo multiplier (PM).
• Read current from PM and CF converter is used.
• Mechanism moves the PS radially and rotate around the axis of radiation
• 8.5 μm thick NE102 plastic scintillator only detect EUV and soft X-rays up to 2keV, but no hard X-rays or UV's are detected.
• Filter made of 385 nm thick Al foil select radiations higher than 400eV



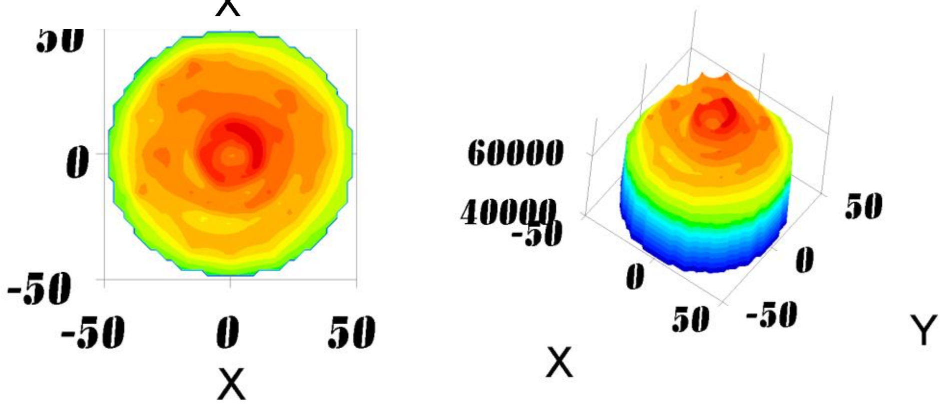


Experimental results on 55nm thick DLC



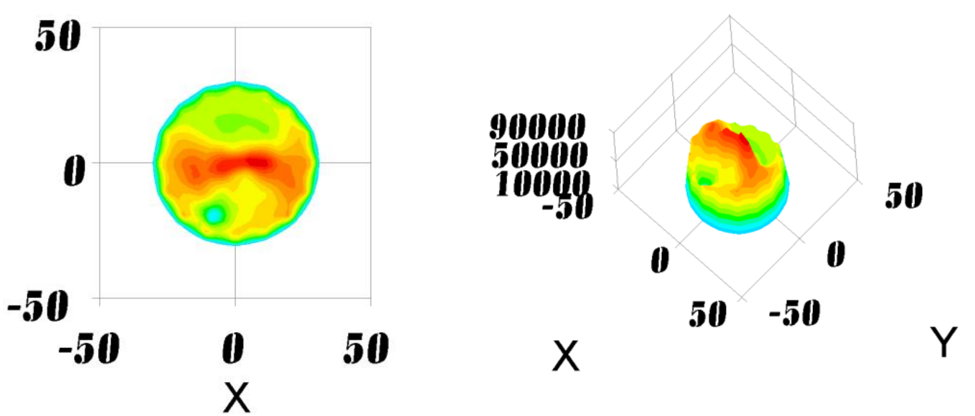
(a)Without Al filter

Photon energy higher than 73eV is detected
2 peaks appears



(b) With Al filter

Photon energy higher than 400eV is detected
Hollow radiation having 3 ridges appears



(c) = (a)-(b)

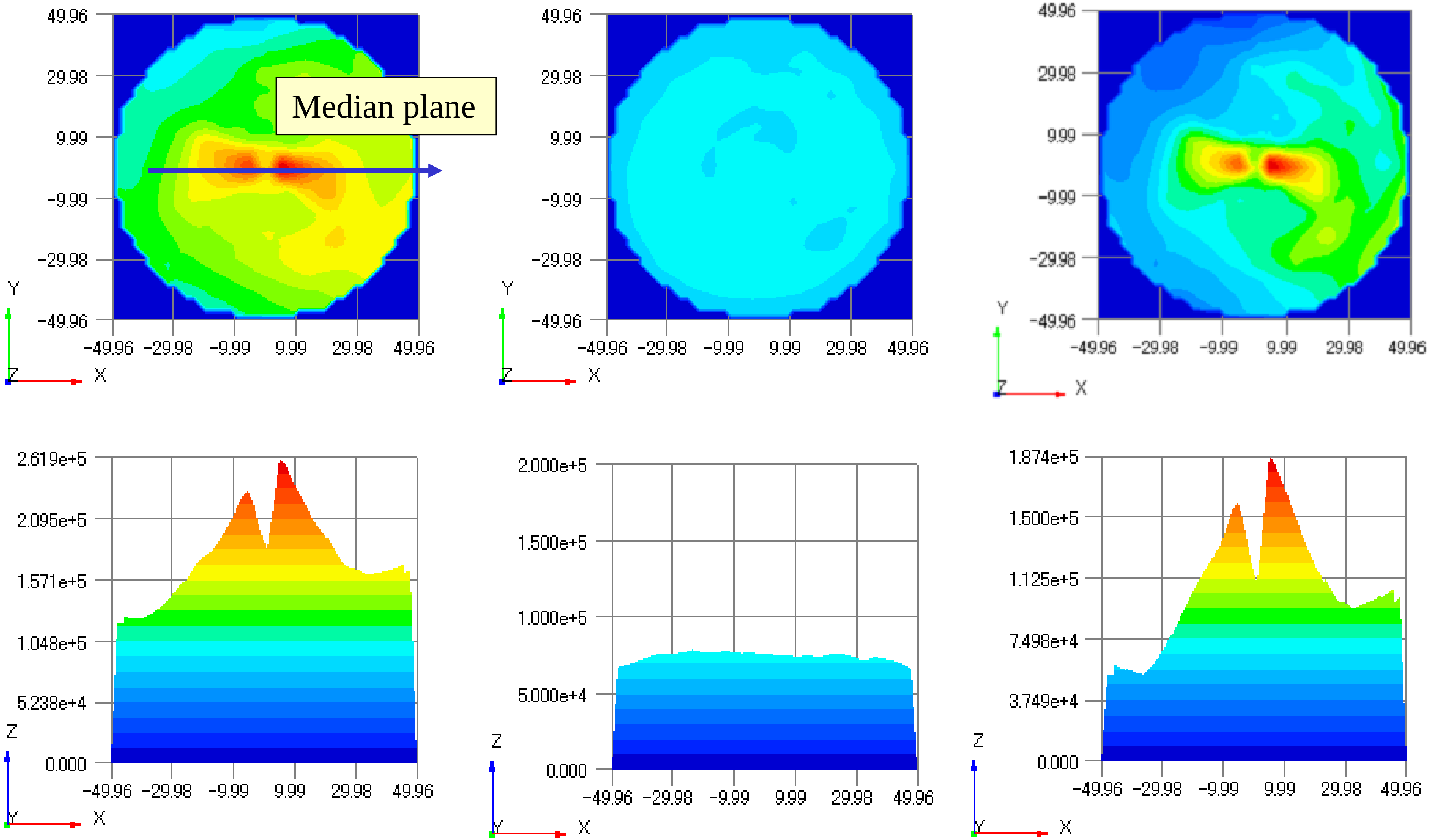
Photon energy range $73eV<E<420eV$ ……… absorption edge of C 277eV is detected

Experimental results on 10μm thick CNT wire (yarn)

A) Measured by plastic Scint.

B) With 0.385um Al filter

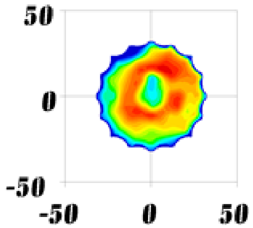
C) A-B 73eV<E<420eV)



Our results are consistent with Rinne theory

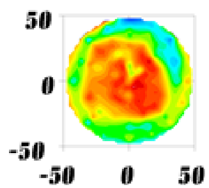
Hollow cone distributions are due to the TR, and directional distribution is due to the SCR

Mo



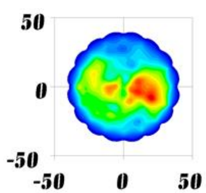
Absorption edges are 2.3keV(L), and 17.5 keV(K)
Radiation spread ~±15mrad hollow cone
no SCR is expected, so this is TR

Sn



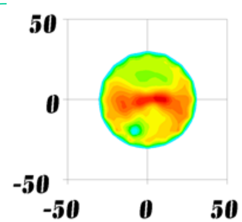
Absorption edges are 3.4keV(L), and 25 keV(K)
Radiation spread ~±20mrad hollow cone
no SCR but TR

Al

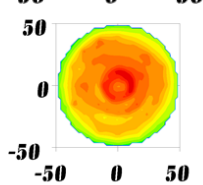


Absorption edge: 1.5keV(K)
SCR is within the detection range

C

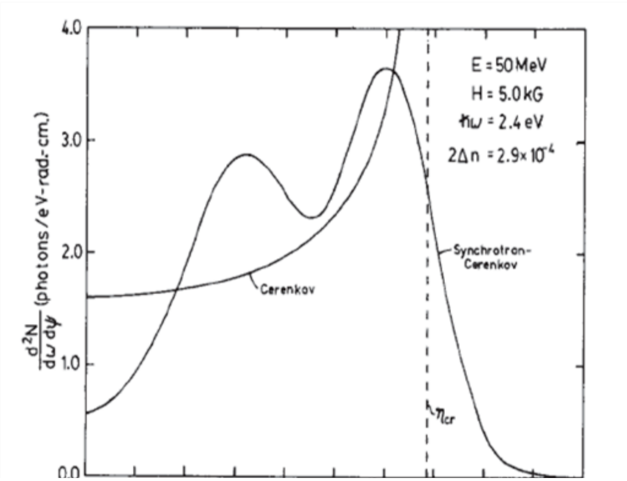


Absorption edge is 277eV(K)
Radiation spread ~±5mrad directional
SCR is detected

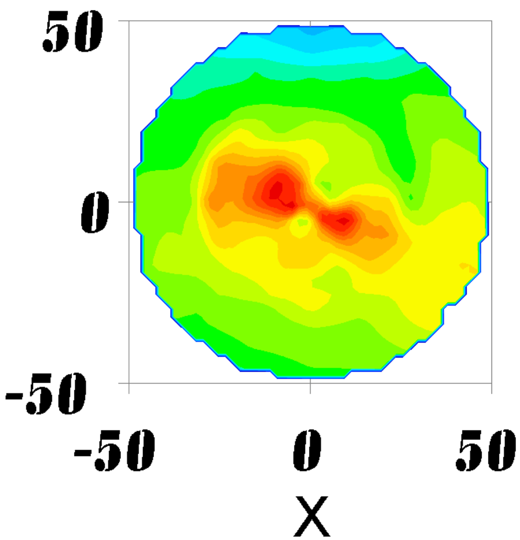


Photon energy higher than 400 eV
Radiation spread ~±30mrad hollow cone
Must be Transition

Comparison with Rynne theory

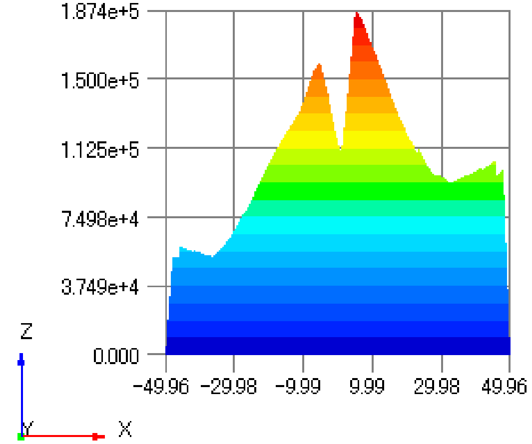


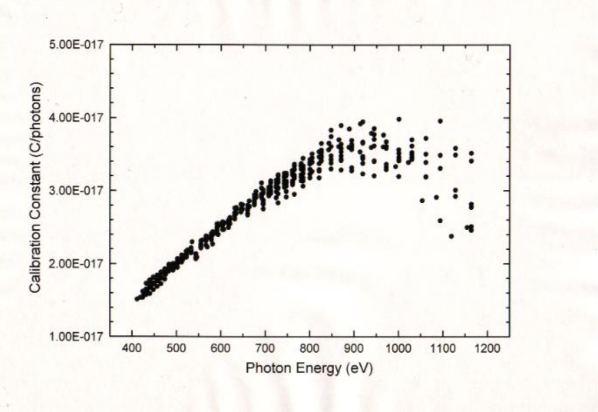
	Our case	theory
E	20	50 MeV
magnetic field	3.3kG	5 kG
photon energy	277 eV	2.4 eV
Obs. or Cal. ψ	5mrad	12 mrad
$\frac{H/E}{h\omega}$	5.9E-4	0.04
$\psi^2 \propto A \frac{H/E}{h\omega} / \sqrt{\Delta n}$	A=4500	A=4500
Δn	0.0011	$1.56\text{x}10^{-4}$



Higher electron energy, lower magnetic field, higher photon energy, higher Δn reduces the radiation spread

Measured EUV power from CNT





Radiated power from the CNT target is 19μA at repetition 70Hz.

Detector efficiency is 0.236[W/A] at the C k-edge energy 277eV.

Transmission rate by filter is 0.925.

Beam current 100mA,

The radiation power/pixel at 1000Hz repetition,

$P_{max} = 19/0.236/0.925 \cdot 1000/70 =$ 3897μW/pixel

Pixel solid angle Ω_{PS} = (3x3)/(720x720)=1.74x10-5 sr.

(detector is 720mm from the source)

Photon density at the peak P_{max}/Ω_{PS} =235W/sr

= 1.29 x 10^{13} photons/s, mrad^2, 0.1%bw

Focus size 3x0.01mm^2 presents the Brilliance

= 4.28 x 10^{14} photons/s, mm^2, mrad^2, 0.1%bw

Average power over the radiation field is 98 mW

Summary of SC radiation

- SC radiation appears at the absorption edge of materials.
- Photon energy is 277eV for C,

  (108 eV for Be targets)
- Radiation spread ψ is $<1/\gamma$. Higher photon energy presents narrower angular spread.
- 20MeV present 5mrad.
- Radiation power over the radiation field is

  98mW/60mrad^2

  at the peak: 235W/sr
- Radiation must be highly coherent.

20 MeV tabletop synchrotron can generate 1KW EUV or soft X

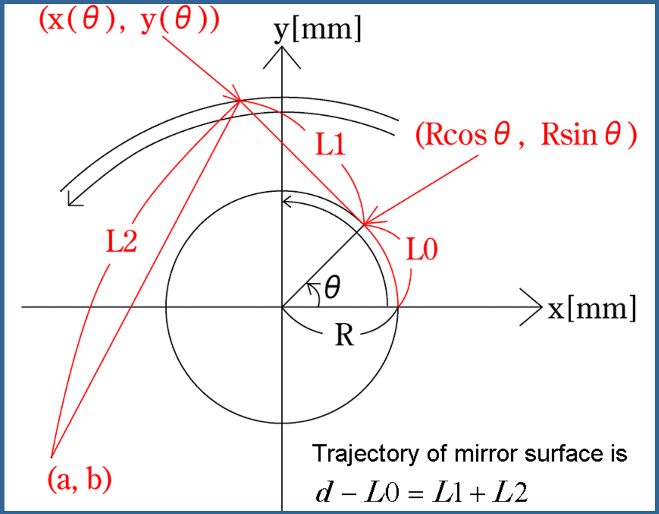
by setting 1000 of strings

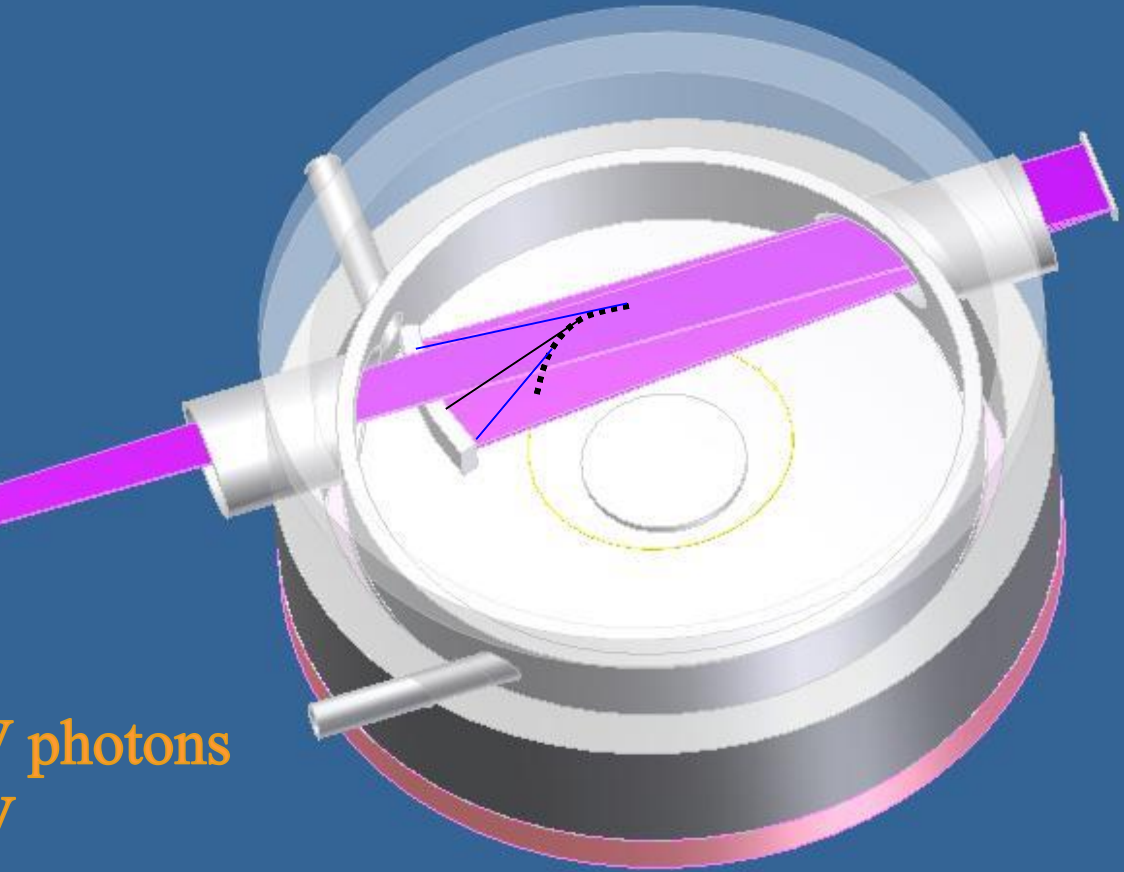
and

by CW continuous injection

1 kW EUV source is feasible

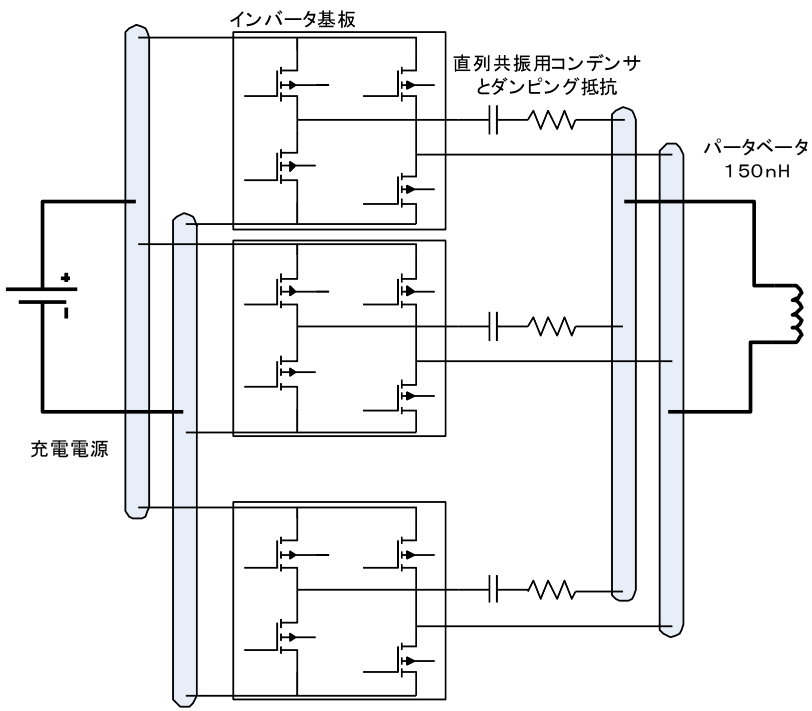
By **setting 1000 of CNT target along the beam orbit**
By **using a magic mirror (quasi ellipsoidal mirror)**

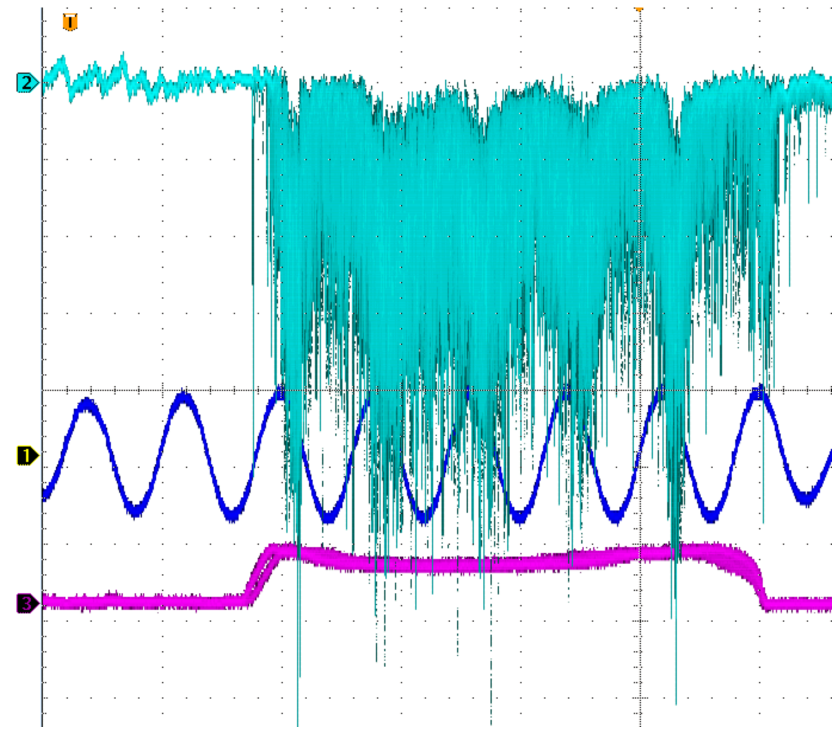




Be generates 108 eV photons
C 277 eV

Continuous CW beam injection scheme is our key technology





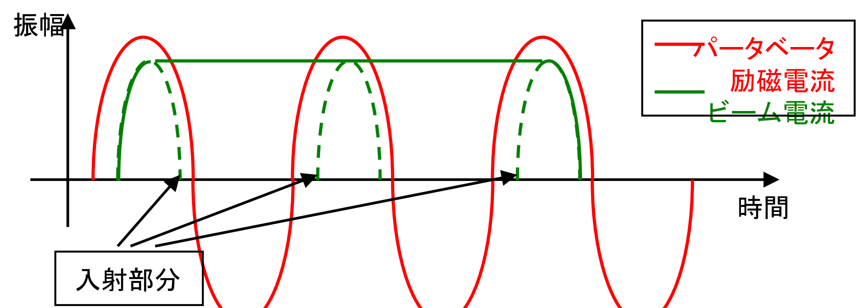
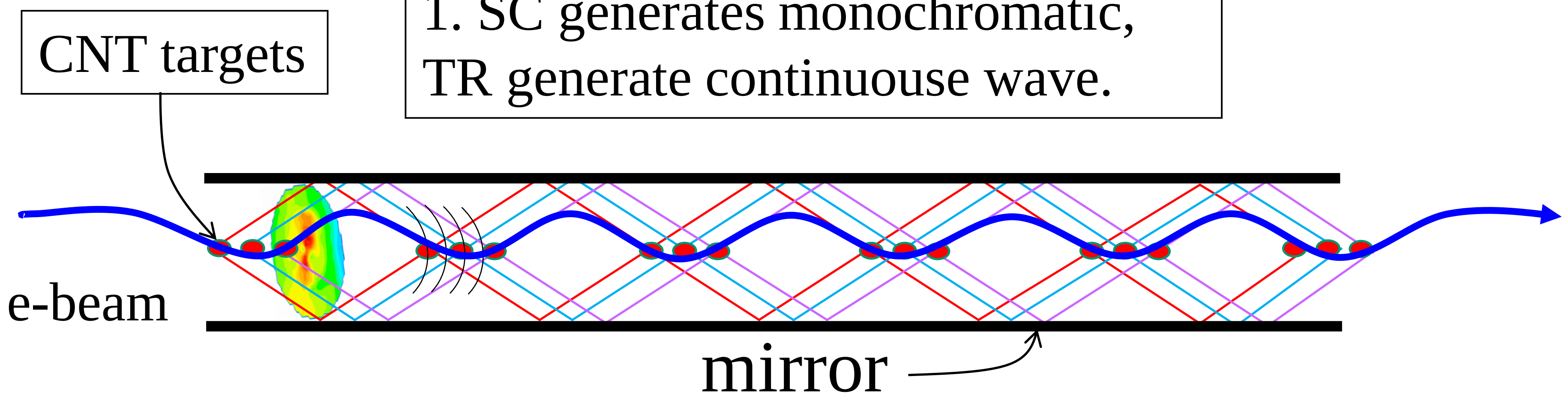


図２　連続発振の入射時のビームとパータベータのタイミング略図。点線が入射する箇所。

Synchrotron-Cherenkov or Transition Radiation Laser

amplification is not required!

1. SC generates monochromatic,
TR generate continuouse wave.



2. Wave front and electron must have the same phase velocity
3. Number of target is 100

Photon power: $P = P_o^{number\ of\ targets}$

EUV laser theory
(Quantum mechanical approach)

IEEE JOURNAL OF QUANTUM ELECTRONICS

Transition Radiation X-Ray Laser Based on Stimulated Processes at the Boundary Between Two Dielectric Media

Kenneth E. Okoye and Hironari Yamada

***Abstract*—This paper analyzes a model of a transition radiation laser based on stimulated emission induced by relativistic electrons crossing the boundary between two media of different dielectric properties. Interaction between the incident radiation and the electrons in this boundary region is taken into account. Phenomenological quantum electrodynamics is applied to derive analytical expressions for stimulated emission and absorption probabilities. Analogs of Einstein's coefficients for the transition processes have also been derived and discussed. It is shown that stimulated emission is greater than absorption. The gain is then calculated.**

***Index Terms*—Absorption, gain, laser, stimulated emission, transition radiation.**

I. Introduction

THE OPERATION of classical laser (CL) is based on the occurrence of population inversion achieved by pumping

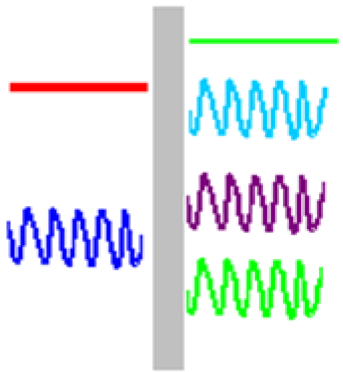
[3], which is emitted when an electron crosses the boundary between two media of different dielectric constants. Resonance transition radiation (RTR) using a periodic multilayer foil or stack foils has been reported by many groups [4]. Use of micro bunched beam is also proposed to generate coherent interaction [5]–[8], but any gain is yet to be reported.

A novel laser scheme proposed by Yamada [9] combines FEL mechanism, Einstein's forced radiation mechanism, and one out of the following: Bremsstrahlung, parametric radiation, or transition radiation. The mechanism which selects the wavelength is introduced in this novel scheme similar to SASE-FEL. One of the periodic interactions of the radiation scheme is shown in Fig. 1. Spontaneous radiation is generated at the first stage by thin targets (not shown). This radiation is then monochromatized by a crystal. When the target itself is made of a thin crystal, monochromatic

Synchrotron-Cherenkov Laser is a classical laser but start with coherent radiation!

Q_i Primary electron

I_i^{ν} Primary photon



Trans. elec. ηQ_i

Spontaneous S_i^{ν}

Induced F_i^{ν}

Trans. photon μI_i^{ν}

$$S_i^{\nu} = \sigma Q_i$$

$$F_i^{\nu} = N\frac{I_i^{\nu}}{4\pi c}B_{10} = N\frac{I_i^{\nu}}{4\pi c}\frac{c^3}{8\pi h\nu^3}A_{10} = S_i^{\nu}\frac{I_i^{\nu}c^2}{32\pi^2 h\nu^3}$$

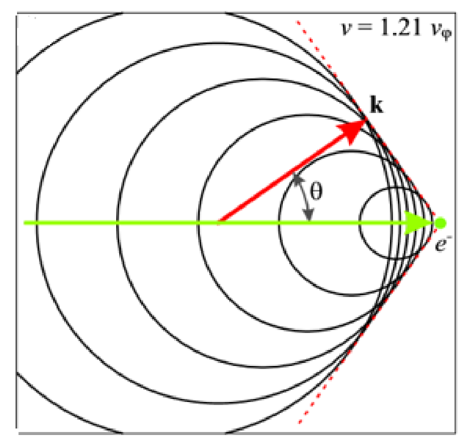
A10, B10 : A,B coefficient

σ: radiation yield

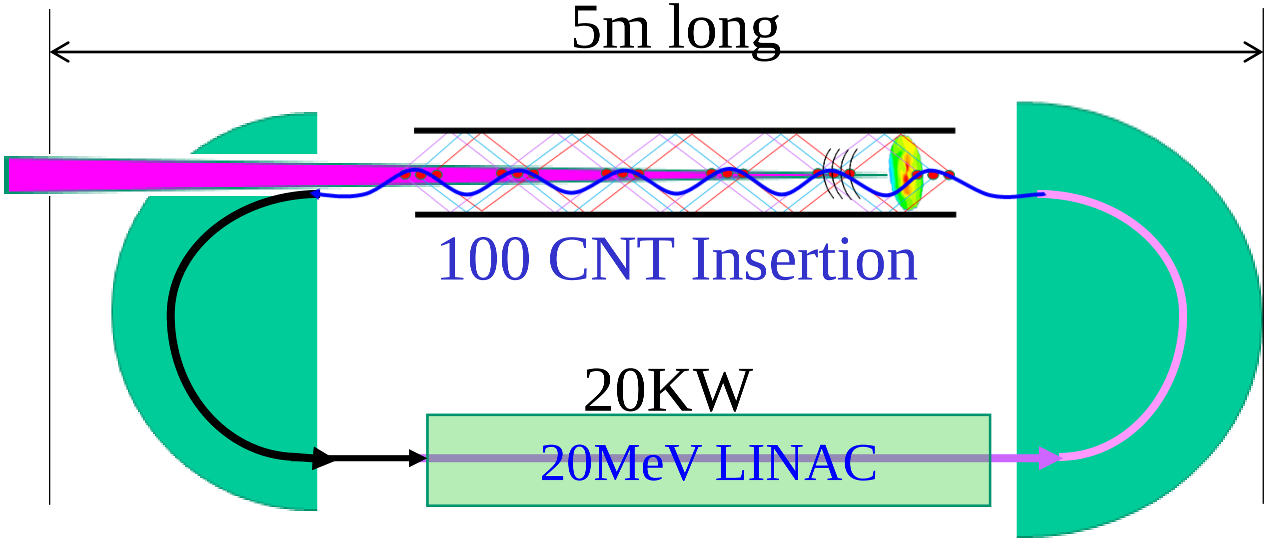
$$I_i^{\nu} = S_{i-1}^{\nu} + F_{i-1}^{\nu} \times \mu I_{i-1}^{\nu} \qquad \kappa = c^2 / 32\pi^2 h\nu^3$$

$$I_i = \sigma\eta^{i-1}Q_0 + \sigma\eta^{i-1}Q_0 \times \kappa\mu I_{i-1}^2$$

$$\sigma\eta^{i-1}Q_0\kappa\mu I_{i-1}^2 > I_{i-1}$$



Accelerator for SCL can be Energy Damping LINAC



Note: Recovery of electron energy is not essential for only 20 MeV 20KW beam.

EUV source Candidates

Radiation mechanism	Accele-rator	Ee	Size	Focal point size	Power Ave.	Power Ettendue /mrad^2	COST (MUS$)	comments
undulator	storage ring insertion	>1 GeV	30m Dia.	20μm dia.	10 mW	25W	30	1KW is not achievable
SASE FEL for X-ray	Normal C Linac	>1 GeV	1km long	100 μm dia.	1J/ pulse	100J/ pulse	300	Average power is low
SASE FEL for EUV but not for soft X	ERL with Super C LINAC	>300 MeV	>20m long	1mm dia.	10 KW	10 KW	300	Feasible but many to be studied
SCR or TR for EUV and soft X	Storage ring	<20 MeV	1mx3m	10μm x 1mm	1 KW	10 KW	5	Existing
	ERL with Normal C		5mx5m		10 kW	1000 KW	10	Feasible but many to be studied

conclusion

SCR or TR with tabletop storage ring for 1KW EUV is ready

and

SCR with ERL

is the way to 10KW EUV or soft X-ray laser